3DHZETRN: A COMPUTER EFFICIENT GCR/SPE SHIELD DESIGN CODE

John W. Wilson[1], Tony C. Slaba[2], Francis F. Badavi[1], Brandon B. Reddell[3], Amir A. Bahadori[3]

[1] Old Dominion University, Norfolk, Virginia USA
[2] NASA Langley Research Center, Hampton, Virginia USA
[3] NASA Johnson Space Center, Houston, Texas USA

Outline

- Overview: Computational/design requirements
- 3DHZETRN formalism (development/verification)
- Connection to complex combinatorial geometry
- Verification with Monte Carlo (MC) codes
  - FLUKA, PHITS, Geant4
- Connection to ray-trace geometry
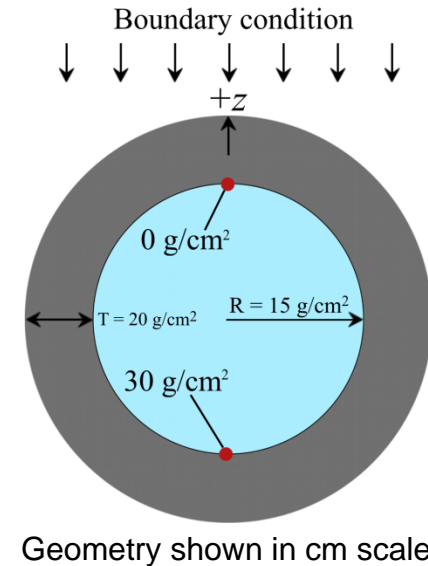- Summary

3DHZETRN Requirements

- 3D extension of HZETRN

  - Extension of bi-directional neutron transport to 3D

  - Maintains computational efficiency

- Must be verified and validated

  - Extensive verification (HZETRN, N = 1, 2)

  - Extensive flight validation (HZETRN, N = 1, 2)

  - Further verification herein (3DHZETRN, N > 2)

- Must integrate into engineering design and Multi-Disciplinary Optimization (MDO) frameworks

- Must have quantified uncertainty for Reliability Design Processes

Methodology Overview

- Direct solution of the Boltzmann equation using method of characteristics with marching procedures

- Interaction model is forward/isotropic with 3D marching procedures over N directions for neutrons
  - Tens of CPU seconds

- Future developments: generalize isotropic component by adding light ion contributions
  - Tens of CPU seconds

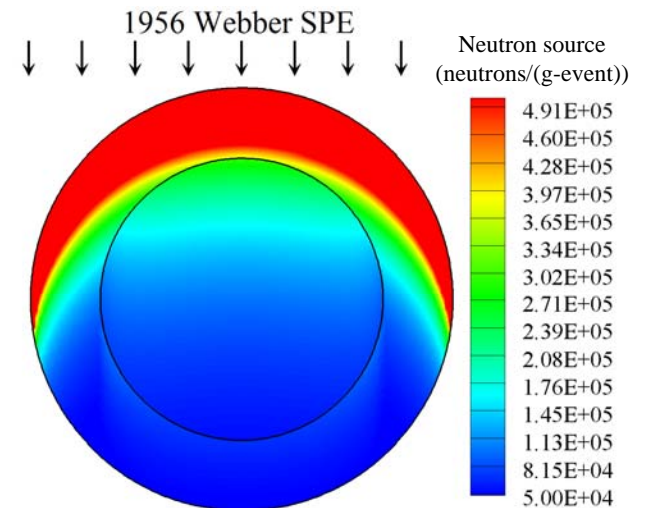- Future developments: end-to-end testing with flight validation

Verification: Sphere benchmark

- Forward/isotropic interaction model

- Test convergence in number of discrete rays needed to describe isotropic neutron field
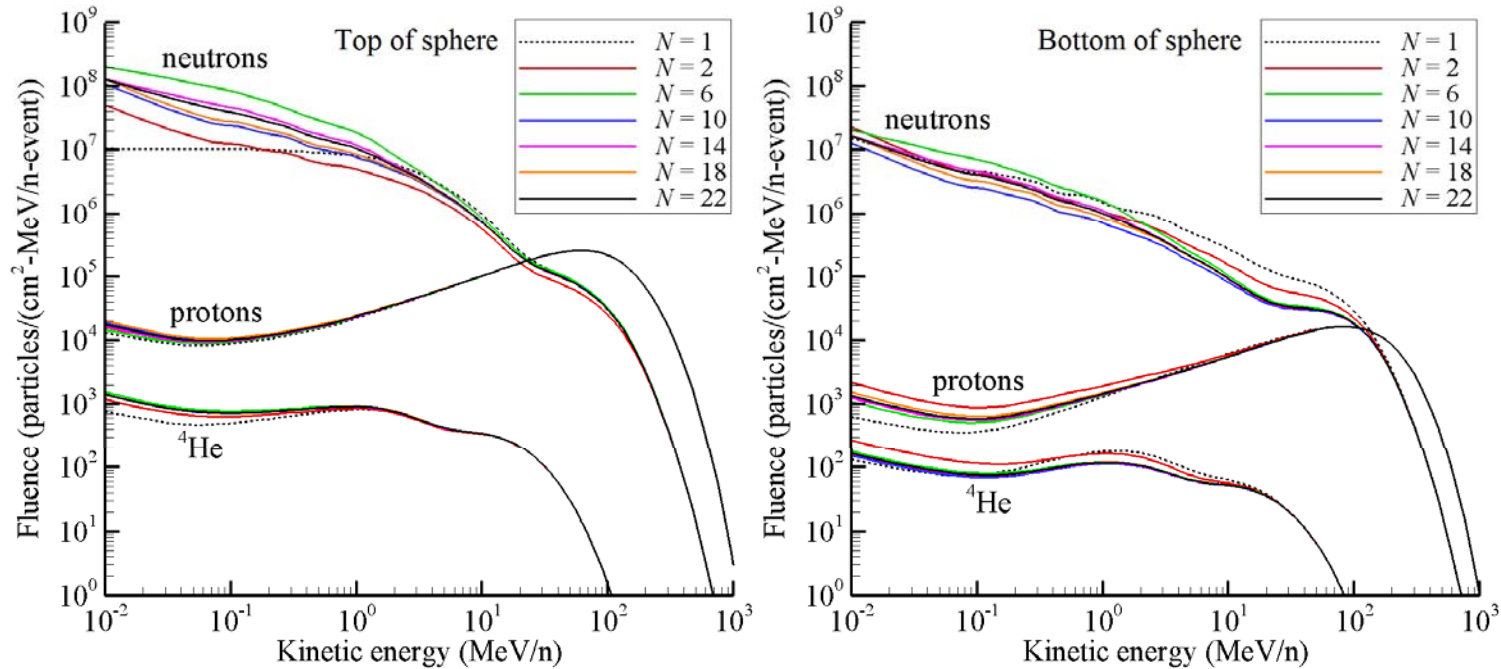
- Verify with Monte Carlo simulations

Boundary condition

$+z$

0 g/cm²

T = 20 g/cm²   R = 15 g/cm²

30 g/cm²

Geometry shown in cm scale

Isotropic neutron source induced by 1956 Webber SPE

$$\sum_k \int \sigma_{nk,iso}(\Omega,\Omega_0,E,E')\phi_{k,for}(x,\Omega_0,E')\,dE' \rightarrow$$

1956 Webber SPE

Neutron source (neutrons/(g-event))

4.91E+05
4.60E+05
4.28E+05
3.97E+05
3.65E+05
3.34E+05
3.02E+05
2.71E+05
2.39E+05
2.08E+05
1.76E+05
1.45E+05
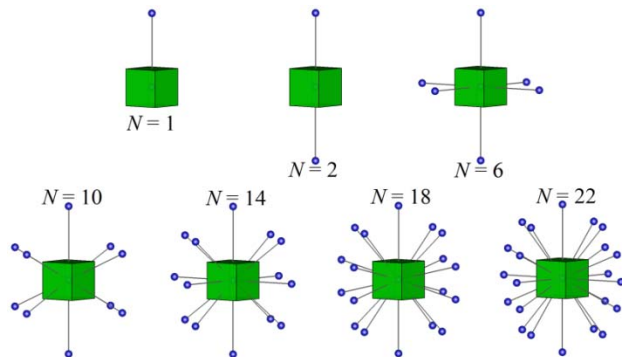1.13E+05
8.15E+04
5.00E+04

Convergence Testing

Nucleon and alpha fluences induced by Webber SPE spectrum
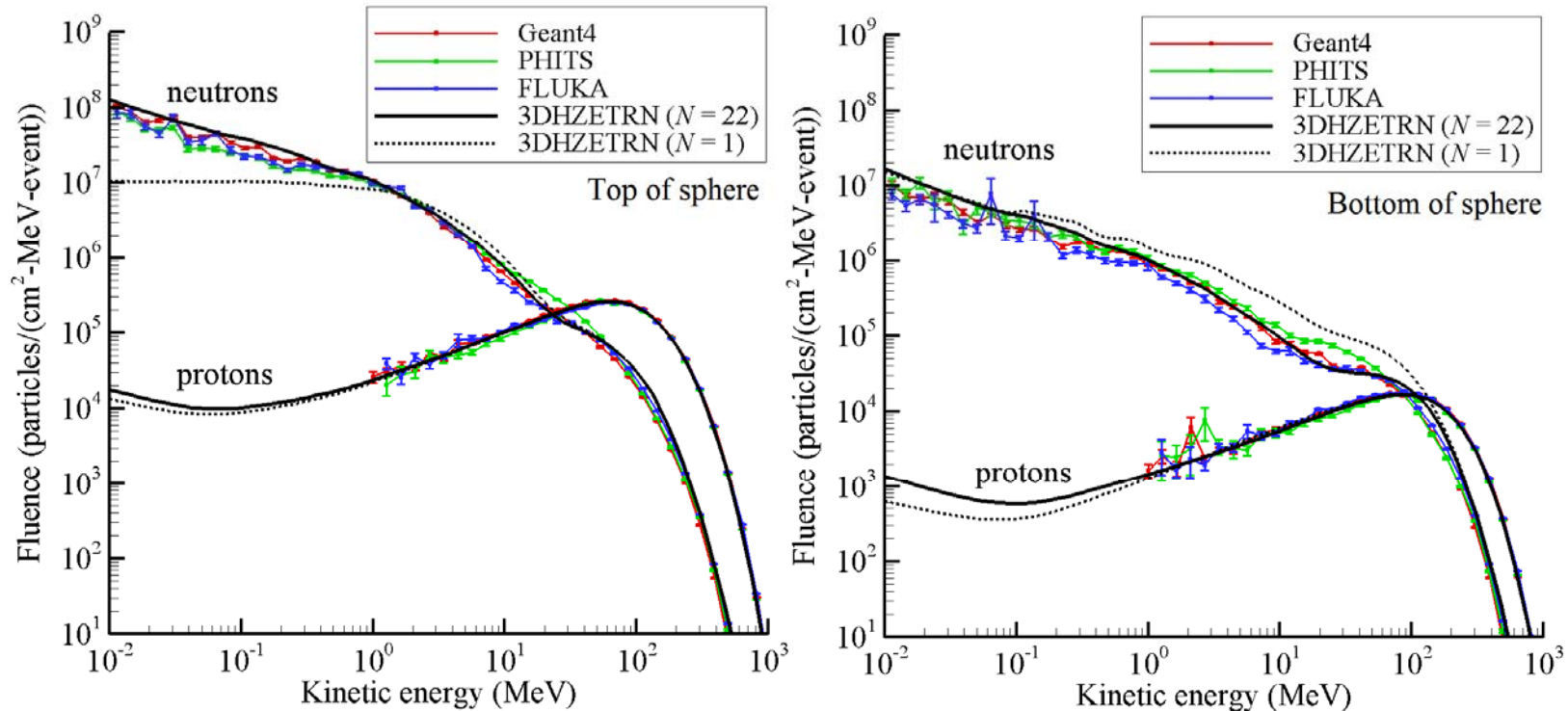
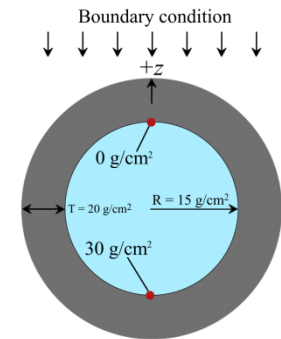

Distributions used to evaluate isotropic particle field

- Solutions for N = 18 and N = 22 are converged
- N = 1 and 2 gives incorrect spectra

Verification: Shielded ICRU Sphere

Nucleon fluences induced by Webber SPE spectrum

- 3DHZETRN (N=22) in close agreement with MC codes
- Large statistical errors in MC results for secondary alpha flux (not shown)
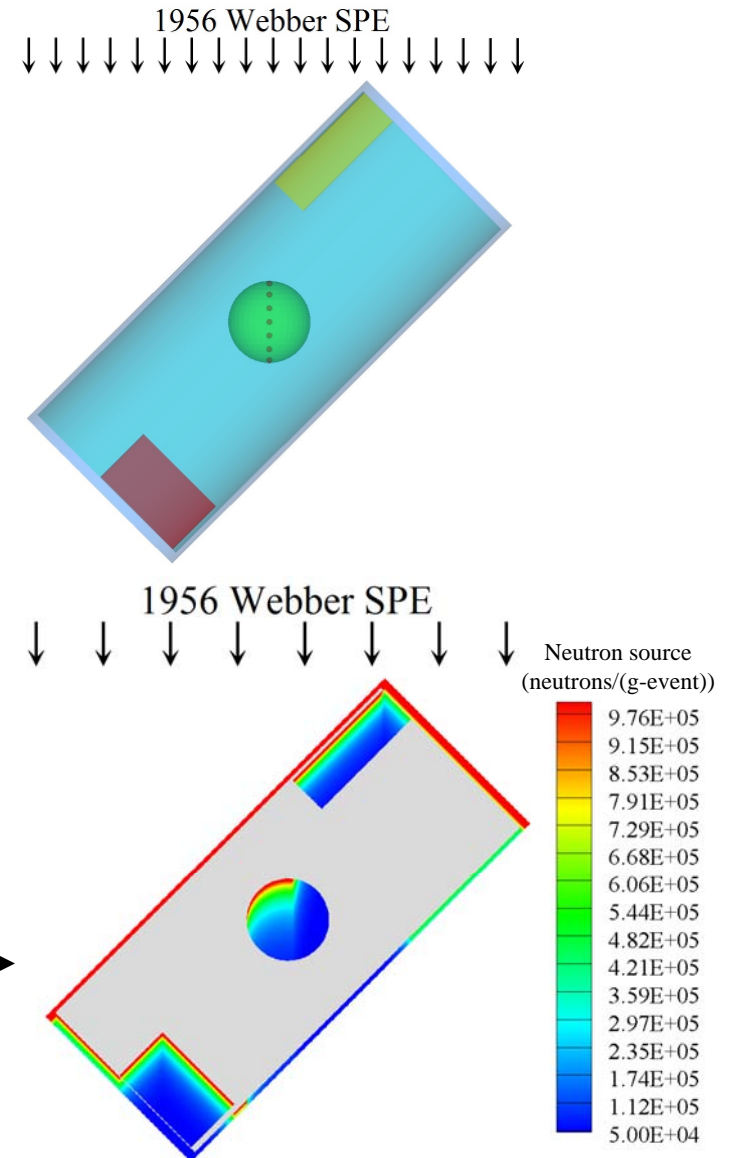
Complex Combinatorial Geometry

- Complex combinatorial geometry with ICRU sphere in an aluminum "spacecraft"

- Test for convergence in number of discrete rays needed to describe isotropic neutron field
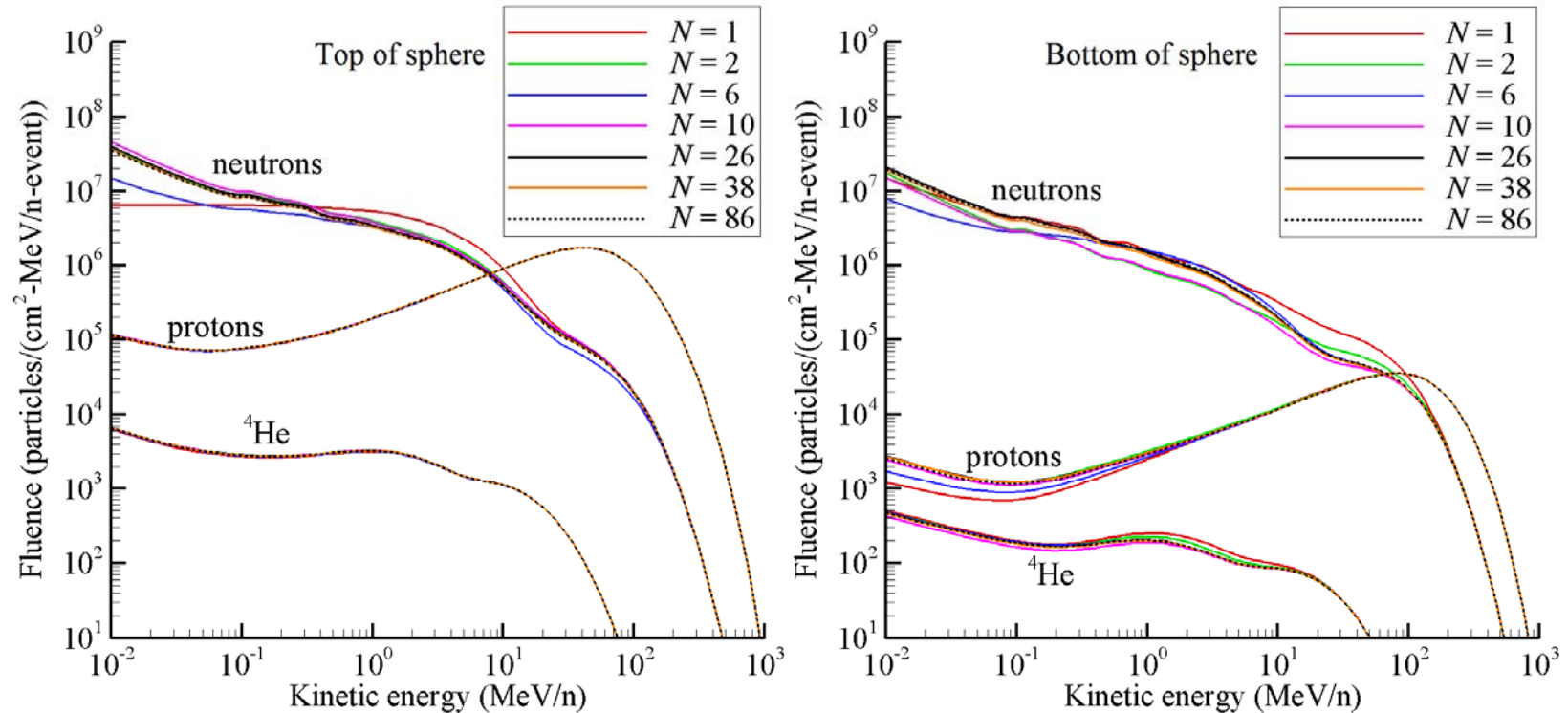
- Verify with Monte Carlo simulations

Isotropic neutron source induced by 1956 Webber SPE ➜

$$\sum_k \int \sigma_{nk.iso}(\Omega, \Omega_0, E, E')\phi_{k.for}(x, \Omega_0, E')\,dE'$$

Convergence Testing
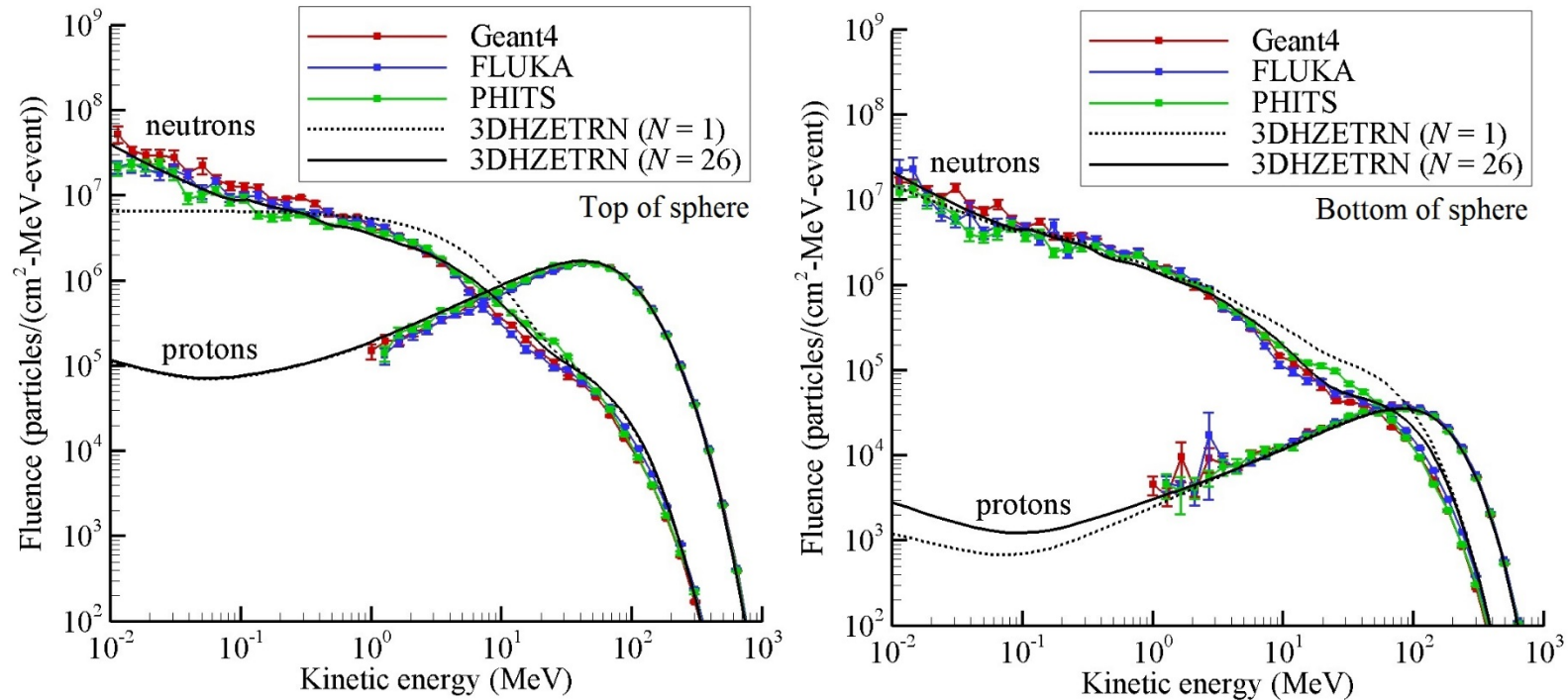
Nucleon and alpha fluences induced by Webber SPE spectrum

- N $\geq$ 26 are clearly converged

Verification

Nucleon fluences induced by Webber SPE spectrum

- Fluctuations in MC neutrons results associated with ENDF elastic resonances
- 3DHZETRN (N=26) significant improvement over straight-ahead approximation (N=1)
- Large statistical errors in MC results for secondary alpha flux
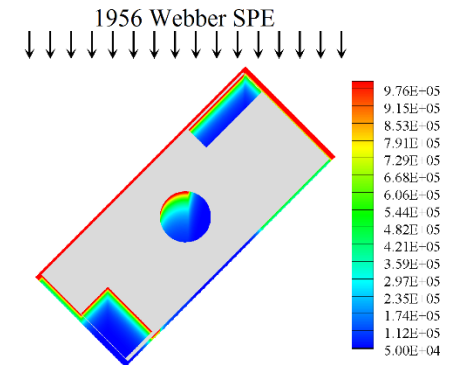
Verification: Webber SPE

Neutron effective dose values (mSv/event) at top and bottom of sphere

	3DHZETRN (N=1)	3DHZETRN (N=26)	Geant4	FLUKA	PHITS
Top	10.31	6.98	5.68	5.68	6.92
Bottom	5.44	3.50	2.77	2.96	3.29

Neutron fluence root mean square relative differences of 3DHZETRN (N=26) and MC codes at top and bottom of sphere

	vs Geant4	vs FLUKA	vs PHITS	MC spread
Top	0.468	0.308	0.269	0.676
Bottom	0.433	0.327	0.339	0.674

CPU seconds required for benchmark calculations
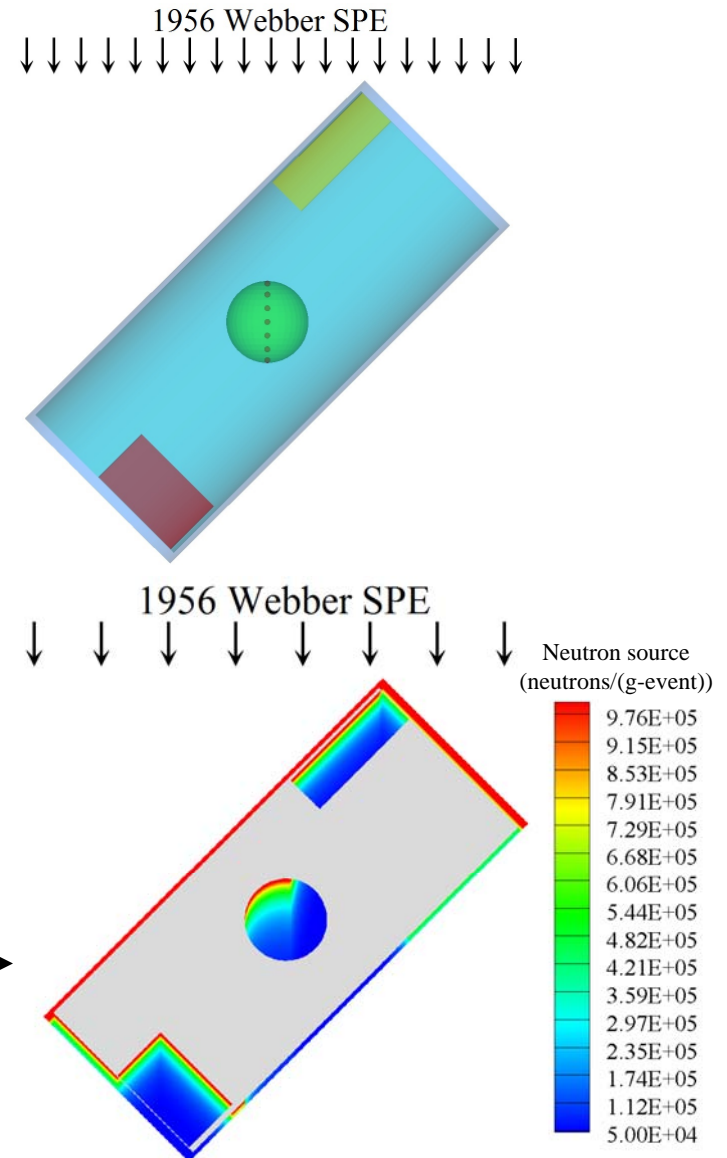Number of histories in MC calculations in parentheses

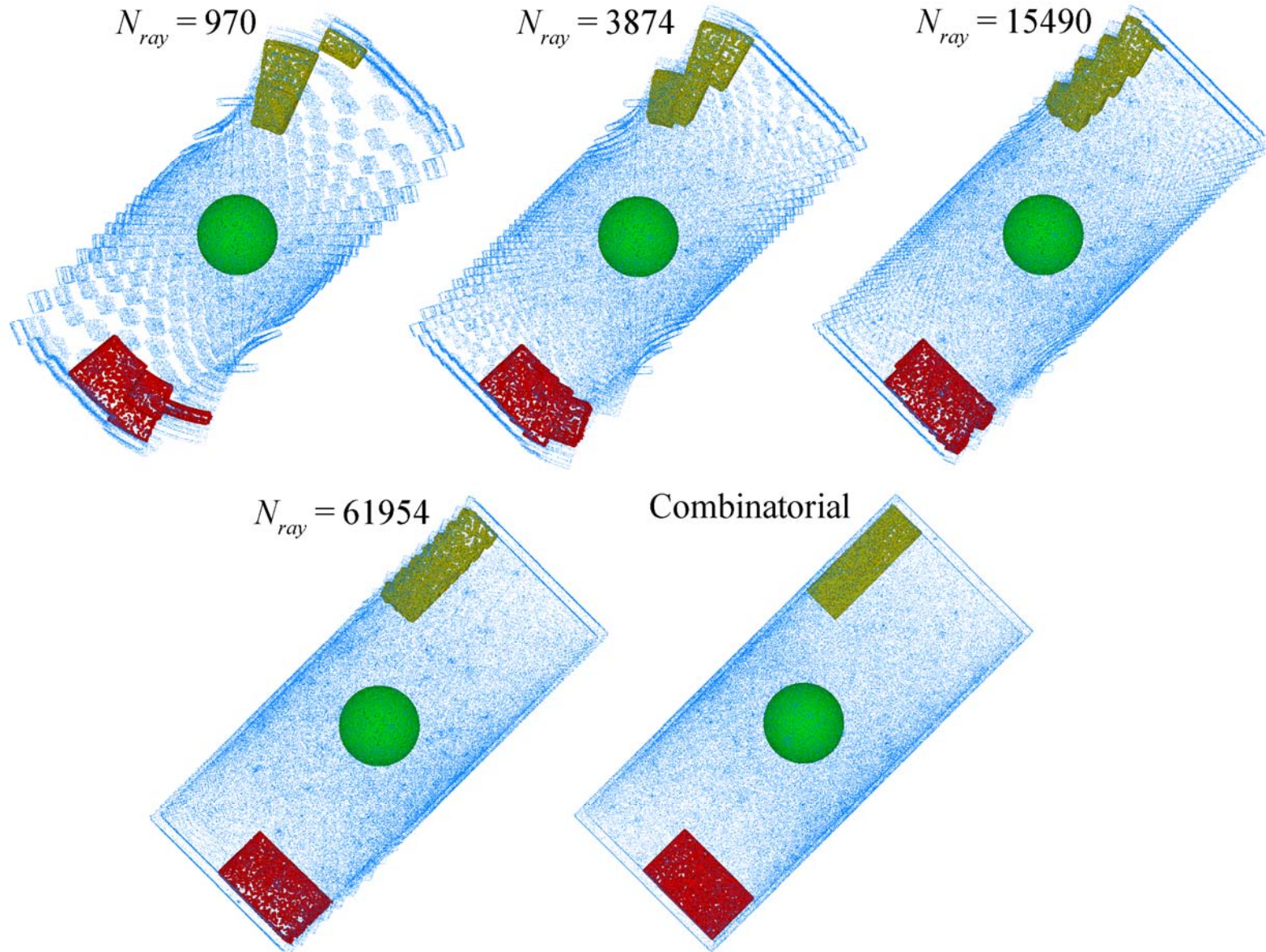|	
3DHZETRN (N=26)	69
Geant4	2×10^8 (1×10^{11})
FLUKA	1×10^8 (4×10^{10})
PHITS	3×10^7 (2×10^{10})

Complex Ray Trace Geometry

- First benchmark in complex combinatorial geometry with ICRU sphere in an aluminum "space craft"
  - External boundary condition applied uniformly down onto sphere along z-axis

- Test for convergence in number of discrete rays needed to describe isotropic neutron field

- Verify with combinatorial geometry simulations

Isotropic neutron source induced by 1956 Webber SPE

$$\sum_k \int \sigma_{nk,iso}(\Omega, \Omega_0, E, E')\phi_{k,for}(x, \Omega_0, E')\,dE'$$

1956 Webber SPE

1956 Webber SPE

Neutron source (neutrons/(g-event))

9.76E+05
9.15E+05
8.53E+05
7.91E+05
7.29E+05
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4.82E+05
4.21E+05
3.59E+05
2.97E+05
2.35E+05
1.74E+05
1.12E+05
5.00E+04

Convergence: Ray-trace Geometry

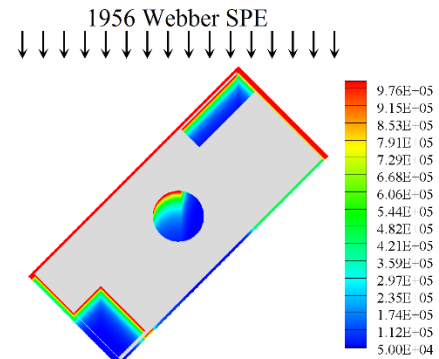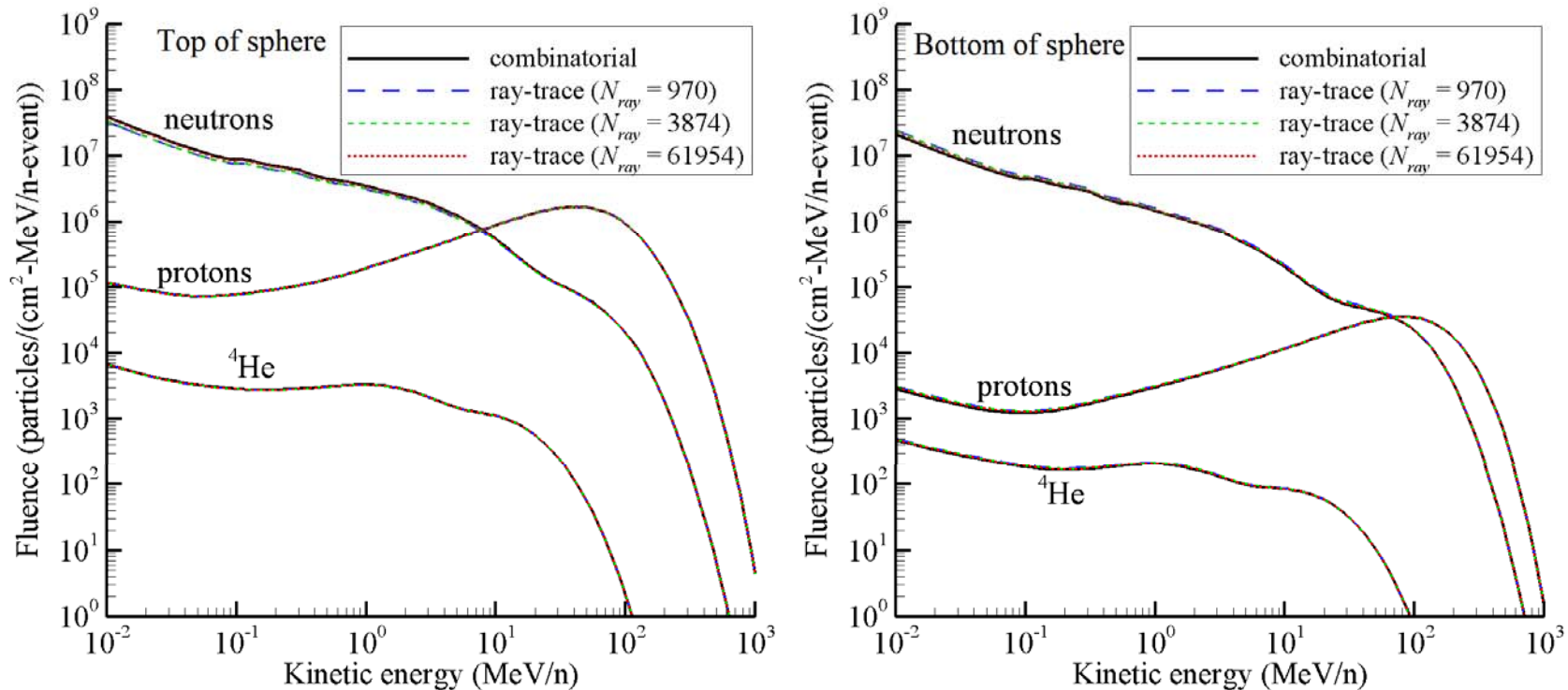$N_{ray} = 970$

$N_{ray} = 3874$

$N_{ray} = 15490$

$N_{ray} = 61954$

Combinatorial

Convergence: Ray-trace Geometry

Nucleon and alpha fluences induced by Webber SPE spectrum in ray-trace and combinatorial geometries

- Results are reasonably converged with N_{ray} = 970
  - Commonly used in OLTARIS

Verification: Combinatorial Geometry

Combinatorial geometry: dose equivalent (cSv/event) at top and bottom of sphere with various N values used for transport

	N=1	N=2	N=6	N=10	N=26	N=38	N=58	N=86
Top	65.90	65.99	65.69	66.08	65.99	65.94	65.86	65.90
Bottom	1.91	1.94	1.80	1.74	1.85	1.83	1.84	1.84

Ray-trace geometry: dose equivalent (cSv/event) at top and bottom of sphere with various N_{ray} values used for geometry (N=26 in 3DHZETRN)

	N_{ray}=970	N_{ray}=3874	N_{ray}=15490	N_{ray}=61954
Top	65.89	65.90	65.94	65.97
Bottom	1.90	1.89	1.87	1.87

Summary and Future Work

- Newly developed 3DHZETRN code includes 3D corrections for neutrons and neutron-induced light ions

- Benchmark comparisons with MC codes showed significant improvement in 3DHZETRN results and close agreement for nucleons
  - Non-trivial differences in nuclear physics models still present

- Current code can work from set of combinatorial geometries

- Extended to engineering ray trace representation of complex geometries
  - Connects to current methodologies used for vehicle design and shield optimization

- Extend to 3D light ion/neutron using isotropic/straight-ahead interaction

- Begin space flight validation

References

(visit John William Wilson at Researchgate)

Formalism and benchmarks in spherical geometries:

1. Wilson, J.W., Slaba, T.C., Badavi, F.F., Reddell, B.D., Bahadari, A.A., Advances in NASA Radiation Transport: 3DHZETRN, *Life Sci. Space Res.*, **2**: 6-22; 2014.

2. Wilson, J.W., Slaba, T.C., Badavi, F.F., Reddell, B.D., Bahadori, A.A., 3DHZETRN: Shielded ICRU Spherical Phantom, *Life Sci. Space Res.*, **4**: 46-61; 2015.

3. Wilson, J.W., Slaba, T.C., Badavi, F.F., Reddell, B.D., Bahadori, A.A., A Study of Neutron Leakage in Finite Objects. *Life Sci. Space Res.,* **7:** 27–38; 2015.

Formalism and benchmarks in inhomogeneous complex geometries:

1. Wilson, J.W., Slaba, T.C., Badavi, F.F., Reddell, B.D., Bahadori, A.A., Solar Proton Transport Within an ICRU Sphere Surrounded by a Complex Shield: Combinatorial Geometry. NASA/TP-2015-218980, 2015.

2. Slaba, T.C, .Wilson, J.W., Badavi, F.F., Reddell, B.D., Bahadori, A.A, Solar Proton Transport Within an ICRU Sphere Surrounded by a Complex Shield: Ray-trace Geometry. NASA/TP-2015-218994, 2015.

http://spaceradiation.larc.nasa.gov/journalarticles.html